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The use of transfer radiometers in validating the visible to shortwave infrared calibrations of radiance sources used by instruments in NASA's Earth Observing System

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Abstract
The quantitative study of climate change over decades requires successive generations of satellite, airborne and ground-based instrumentation carefully calibrated against a common radiance scale. In NASA's Earth Observing System (EOS) program, the most common sources used in the laboratory radiance calibration of satellite, ground-based and airborne instruments operating in the reflective solar wavelength region of 400–2500 nm are integrating spheres and diffuse reflectance panels illuminated by irradiance standard lamps. Since 1995, the EOS calibration program operating within NASA's EOS Project Science Office (PSO) has enlisted the expertise of the National Institute of Standards and Technology (NIST), the University of Arizona Optical Sciences Center's Remote Sensing Group (UA), Japan's National Research Laboratory of Metrology (NRLM) and NASA's Goddard Space Flight Center (GSFC) in an effort to validate the radiance scales assigned to sources used in the prelaunch calibration of EOS instruments and to critically examine the operation, repeatability and stability of those sources. Radiance scale validation is accomplished using stable transfer radiometers operating at visible to shortwave infrared wavelengths and calibrated and characterized by each institution using a variety of techniques. In the 10 comparisons performed since February 1995, the agreement between the radiance measurements of these transfer radiometers is ±1.80% at 411 nm, ±1.31% at 552.5 nm, ±1.32% at 868.0 nm, ±2.54% at 1622 nm, and ±2.81% at 2200 nm ($\sigma = 1$).

1. Introduction

NASA's Earth Observing System (EOS), established in 1991 through a presidential initiative, is an integrated international long-term instrument program for Earth remote sensing, using many different platforms and satellites. The primary goal of EOS is to advance the understanding of the Earth and its changes as a system through careful examination of the components of the system and their interactions. This goal is achieved by the acquisition and analysis of data from the numerous EOS satellite instruments located on the same and successive platforms. The correct interpretation of these satellite data requires the ability to distinguish between on-orbit instrumental changes and actual physical changes in the Earth processes being monitored. The ability to make this distinction depends on careful calibration of the instruments against common physical standards before launch, successfully transferring those calibrations through launch,

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and correctly monitoring those calibrations on-orbit over the lifetime of the mission. On-orbit satellite instrument calibration is typically monitored using on-board calibration systems and ground-based and airborne vicarious calibration (VC) instruments deployed on or above spectrally and spatially featureless Earth sites at the times of over-passes by the satellite instrument.

In EOS, the prelaunch or predeployment radiometric calibrations of satellite and VC instruments are performed at the satellite instrument-builders' facilities and at the VC instrument metrology laboratories respectively. In the visible to shortwave infrared wavelength region, the uniform radiance sources of choice for these calibrations are internally and externally illuminated integrating spheres and diffuse reflectance panels illuminated by irradiance standard lamps. EOS instruments are required to trace their calibrations to either source-based or detector-based standards maintained by the national standards laboratory of the country of origin of the instruments. For example, the prelaunch calibrations of the United States' Moderate Resolution Imaging Spectroradiometer (MODIS) and the Japanese Advanced Spaceborne Thermal and Emission Reflection Radiometer (ASTER) on the EOS Terra platform are traceable to standards maintained by the National Institute of Standards and Technology (NIST) and the National Research Laboratory of Metrology (NRLM) respectively.

In 1995, the EOS calibration program as part of NASA's EOS Project Science Office (PSO), enlisted NIST to help coordinate a measurement assurance program (MAP) [1–3] to validate the radiance scales assigned to uniform sources by the satellite instrument builders and VC laboratories. In this process, NIST has built, characterized, calibrated and maintained stable radiometers operating in the visible/near, infrared, shortwave infrared and thermal infrared wavelength regions. These radiometers are designed to travel to the EOS instrument builder and VC facilities and participate in radiometric measurement comparisons. In addition to the NIST radiometers, transfer radiometers from the University of Arizona Optical Sciences Center Remote Sensing Group (UA), NRLM, NASA's Goddard Space Flight Center (GSFC) Sea-viewing Wide Field-of-View Sensor (SeaWiFS), NASA's GSFC Landsat Enhanced Thematic Mapperplus (ETM+), NASA's GSFC Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) projects, and NASA's GSFC Radiance Calibration Facility have participated in many of these comparisons. This paper presents and discusses the agreement between the transfer radiometer radiance measurements obtained from 10 radiometric comparisons on 14 radiance sources held from February 1995 to April 2001.

2. Radiometers

The radiometers which have participated in the EOS radiometric measurement comparisons are presented in table 1. Included in table 1 are the radiometers' institutional affiliations, operating wavelengths and bandwidths. A description and calibration of each radiometer is given briefly below.

2.1. NIST Visible Transfer Radiometer

The NIST Visible Transfer Radiometer (VXR), built in 1996 by NIST for the EOS PSO, is a six-channel filter radiometer similar in design to the SeaWiFS Transfer Radiometer (SXR) [4]. The VXR filters were chosen to coincide with several visible and near-infrared bands of the MODIS, ASTER and Multispectral Imaging Specroradiometer (MISR) instruments on the EOS Terra platform. Prior to December 1999, the VXR was calibrated for radiance using an Optronic Laboratory Incorporated OL420 integrating sphere source located in NIST's Facility for Automated Spectroradiometric Calibrations (FASCAL) [5]. Before December 1999, the measurement uncertainties for the VXR were estimated to be 2% ($k = 1$) for all but the 870 nm channel. For that channel, the uncertainty was estimated to be 3% ($k = 1$) [6]. From December 1999 to December 2001, revised calibration coefficients were applied to the VXR radiance measurements [7]. In December 2001, the VXR was calibrated for spectral radiance responsivity in NIST's Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) facility [8]. The measurement uncertainties resulting from the SIRCUS calibration improved to 0.7% at 411 nm and 0.5% at 870 nm ($k = 1$).

2.2. NIST Shortwave Infrared Transfer Radiometer

The NIST Shortwave Infrared Transfer Radiometer (SWIXR) [9] is a scanning spectroradiometer employing a double monochromator and using all-reflective input optics and a liquid-nitrogen-cooled indium antimonide (InSb) detector. The operating wavelengths for the SWIXR range from 800 nm to 2500 nm, with a variable bandwidth depending on the slit widths. In June 1998, the SWIXR was calibrated at NIST against an OL450 integrating sphere source calibrated for spectral radiance using a variable temperature blackbody located in the NIST Radiance Temperature Laboratory [10]. In the 1998 calibration, the radiance measurement uncertainty of the SWIXR was 4.5% ($k = 1$). Subsequent calibrations of the SWIXR were performed using the NIST Portable Radiance (NPR) source [11] calibrated in the NIST Radiance Temperature Laboratory, resulting in the measurement uncertainties of 1.7% ($k = 1$). The SWIXR is calibrated for wavelength before, during and after all comparisons using atomic pen-lamps.

6. Summary

From February 1995 to April 2001, ten transfer radiometers participated in a radiometric measurement comparison with the goal of validating the radiance scales assigned to 14 uniform radiance sources used in the calibration of EOS satellite, ground-based and airborne instruments. The transfer radiometers were independently calibrated at their home institutions using a variety of techniques. The agreement between the radiance measurements made by these radiometers was ±1.80% at 411 nm, ±1.31% at 552.5 nm, ±1.32% at 868.0 nm, ±2.54% at 1622 nm and ±2.81% at 2200 nm ($\sigma = 1$), within the combined uncertainties of the radiometer measurements. This level of agreement is sufficient to validate the radiance scales of EOS sources with typical radiance calibration specifications of ±3.0% ($k = 1$).